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COST ESTIMATING RELATIONSHIPS FOR NAVAL SURFACE SHIP ELECTRONIC WARFARE EQUIPMENT

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

COST ESTIMATING RELATIONSHIPS FOR NAVAL SURFACE SHIP ELECTRONIC WARFARE EQUIPMENT

by

Raymond Edward Moore III

March 1975

Thesis Advisor: J.K. Hartman

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Cost Estimating Relationships for Naval

Surface Ship Electronic Warfare Equipment

by

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the
requirements for the degree of

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I. INTRODUCTION

Traditionally cost estimates for military equipment have been derived through engineering techniques. These techniques are extremely time consuming and require detailed information about the proposed equipment. It has been found in recent years that estimates made using Cost Estimating Relationships (CERs) based on equipment characteristics or parameters require less time. Some experts maintain that they are at least as accurate as the engineering estimates as long as care is taken in choosing the CER.

An advantage of CERs is that since a proper CER is developed from historical data on similar equipment, it takes into account hidden costs which would be impossible, practically speaking, to separate out, and which are perhaps not considered when making engineering estimates.

Before one begins estimating costs by the parametric method, one must locate or develop a CER which adequately represents the equipment in question.

The objective of this thesis is to develop such CERs to be used in estimating the costs for development, procurement, and installation of three design-to-price electronic warfare suites currently under development by Raytheon and Hughes for the United States Navy, and to estimate those costs for the proposed systems.

The CERs are developed from data presented in Ref. 1 utilizing BIMEDO2R, a stepwise linear regression program developed by the University of California at Los Angeles (UCLA). This program considers all independent variables available and, at each step, includes in the equation the one which is most highly correlated with the dependent variable for the first step or the one with highest partial correlation with the previous step for all succeeding steps. This process may also remove a variable if that variable's F-value drops below the F-value to remove, designated for the particular regression, as more variables are added to the equation. More detailed information concerning BIMEDO2R is contained in Ref. 2.

Section II of this thesis concerns the assumptions made about the data and explanations of the various parameters and variables available in the data base.

The development of the CERs is presented in Section III along with an example demonstrating what can happen in linear regression if the independent variables in the equation are highly inter-correlated. Also included is an example of the use of a graphical method of selecting independent variables by Mallows found in Ref. 3.

The CERs developed in Section III are used in Section IV to estimate the cost of the proposed systems and a comparison is made of those costs with the ones estimated in Ref. 1.

The Appendix presents the data matrix, refers to its source and describes adjustments that were made to the original data.

II. DESCRIPTION OF THE MODEL

The data for this thesis consists of the costs and characteristics of 21 electronic warfare (EW) systems developed from 1962 to 1974. These systems represents all of the major surface ship EW systems developed for the U.S. Navy during that time period.

A. ASSUMPTIONS

The following are assumptions made concerning the data used in this thesis.

1. All of the figures in the data taken from Ref. 1 are correct except as noted in the Appendix. It should be pointed out that this data differs greatly in some areas from the values found in Ref. 4, however, such differences can be explained by what aggregation of equipment one is referring to, such as, is one interested in the price of a whole suite or just the black box without antennas, etc. The data used in this thesis describes the total system for one ship.

2. Costs for the individual equipments are independent of the costs of all other pieces of equipment. It is felt that this assumption is valid since cost of development of follow-on equipment which was a modification of existing equipment was adjusted where possible by Mitchell and Mullins for Ref. 1. Where such adjustment was found to be impossible, those data points were excluded from the data matrix.

B. PARAMETERS AND VARIABLES

The parameters and variables used in this thesis are described below. Dollars are measured in thousands of 1975 dollars.

1. Development Cost (DEVC) includes the cost of Research, Development, Test and Evaluation (RDT & E) of the equipment in question.

2. Procurement Cost (PRDC) is the cost of producing the first unit of the equipment.

3. Installation Cost (INST) is the average cost of installing the equipment on the surface ships for which it was designed.

4. Year of Development (YR) is a measure of the number of years from the base year of 1969 to the year of development. This variable is negative for equipment developed prior to 1969.

5. Weight (WT) is the weight in pounds of the equipment.

6. Volume (VOL) is the volume in cubic feet of the equipment.

7. Sensitivity (SENS) is the receiver sensitivity of the equipment measured in decibels. All values are negative.

8. Power Output (KWO) is the power output of the active equipments measured in kilowatts. This variable is zero for passive equipment.

9. Gain (GAIN) is the antenna gain measured in decibels.

10. Active (ACT) is a dummy variable with a value of one for active equipment and zero for passive ones.

11. Complexity (CPLX) is a measure of complexity for the equipment, in this data base, ranging from one to three, one signifying relative simplicity and three extreme complexity. The source of this variable is discussed in the Appendix.

12. Large (LG) is a dummy variable with a value of one for equipment designed for guided missile destroyers (DDG) and larger ships and zero otherwise.

13. Small (SM) is a dummy variable with a value of one for equipment designed for destroyer (DD) and smaller ships and zero otherwise. For equipment designed for ships in both categories, both variables LG and SM are one.

C. FORM OF THE MODELS

Each model developed in this thesis is a linear regression equation containing one dependent cost variable, an intercept term and any number of the independent variables described above, numbers four through thirteen inclusive.

$$COST = a_o + a_4\, YR + a_5\, WT + \ldots + a_{13}\, SM$$

From examination of the residual plots at various stages during the development, there was no indication that polynomial or other transformations should be used.

III. DEVELOPMENT OF COST ESTIMATING RELATIONSHIPS

With each CER, work was begun by examination of the correlation matrix and scatter plots of dependent versus each independent variable for those equipments for which data were available. Next, the data was fed into the BIMEDO2R stepwise linear regression program. Regression analysis was done with and without a constant term, that is without and with a zero intercept. In each case the fit was considerably better with a constant included; consequently, the zero intercept models were discarded. BIMEDO2R may be controlled as to the number of steps taken by designating a particular number of steps or by setting values for F-level for inclusion and deletion. Setting F-levels allows the variables to enter the model one at a time as long as their F-level to enter for the individual variable is higher than the level designated. If adding a new variable causes the F-level of a previously entered variable to decrease below the level set for deleting, that previously entered variable will be removed. In order to observe as much of the interaction as possible during the early analysis, no maximum number of steps was specified and F-levels were set at 0.01 for inclusion and 0.005 for deletion. When certain models appeared to be of interest, F-levels were increased to more realistic levels and later the maximum number of steps was designated in order to restrict the model. During this phase, residuals were listed and plotted against

the computer value for the dependent variable, and each of the independent variables. Each residual plot was examined for points that appeared to be outliers and for any indication of a need for any type of transformation. Eventually a best model was selected to be the CER for each of the three costs.

In the statistics given after each CER, the F ratio is the test value for the hypothesis that the regression is not significent. If the F ratio is larger than the table value, the hypothesis is rejected and the regression is significant. The F value for each independent variable is used to test the hypothesis that the coefficient of the variable in question equals zero. For instance, if at a particular step there are three independent variables in the model, the F value for each variable is a measure of how much is lost by assuming that the model only includes the other two variables. The hypothesis is rejected if the table value is less than the F value.

A. DEVELOPMENT COST

Development costs were available for twelve (12) pieces of equipment. The correlation matrix for those equipments, listed below, was examined.

DEVC	YR	WT	VOL	SENS	KWO	
1.000	0.384	0.685	0.772	-0.014	0.299	DEVC
	1.000	0.283	0.387	0.162	0.443	YR
		1.000	0.870	0.627	0.640	WT
			1.000	0.468	-0.739	VOL
				1.000	-0.692	SENS
					1.000	KWO

GAIN	ACT	CPLX	LG	SM	
0.213	0.124	0.846	-0.214	-0.108	DEVC
-0.251	0.443	0.631	-0.328	-0.426	YR
0.068	0.511	0.620	-0.018	-0.368	WT
-0.080	-0.609	-0.821	0.326	0.113	VOL
0.048	-0.749	-0.077	0.075	0.253	SENS
-0.172	0.737	0.491	-0.507	0.082	KWO
1.000	0.067	-0.003	-0.014	0.294	GAIN
	1.000	0.423	-0.507	-0.098	ACT
		1.000	-0.449	-0.185	CPLX
			1.000	-0.577	LG
				1.000	SM

Weight, volume, and complexity are highly correlated with development costs. However, since weight and complexity are also very highly correlated with volume, one must insure that if weight and complexity are included in the final model, volume is not and vice versa.

When the data was processed by BIMEDO2R, the first four steps brought in CPLX, ACT, WT, and GAIN in that order. In each step the equation appeared acceptable; however, step four presented the best model. The CER at that step was:

$$\text{DEVC} = -7474.87891 + .30165\ \text{WT} + 142.60353\ \text{GAIN} - 3457.53076\ \text{ACT} + 4757.61719\ \text{CPLX}$$

which had the following statistics:

$R^2 = .9287$

R^2 (adjusted) is a monotonic increasing function with a final value of .888.

Standard error of estimate = 1396.3611

Mean value of the dependent variable = 3802.3

F ratio = 22.782

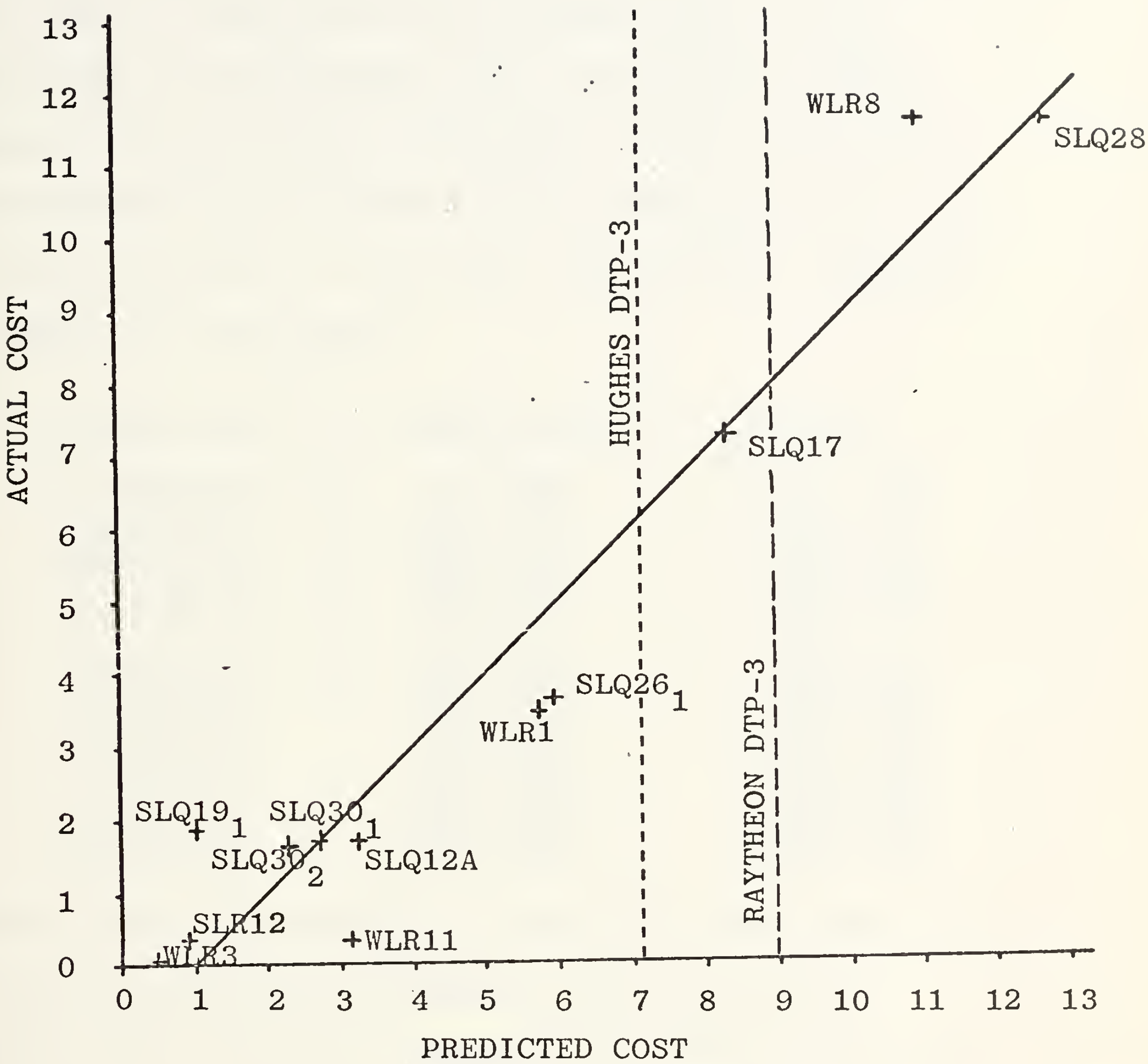
Table value $F_{(.95;\ 4,\ 8)} = 3.84$

F value for each independent variable is:	WT 8.8495
	GAIN 4.5523
	ACT 12.8525
	CPLX 35.1702

Table value $F_{(.90;\ 1,\ 8)} = 3.46$

This model is statistically appealing and intuitively reasonable. The negative sign on the constant is acceptable unless one is attempting to predict the development cost of a very light, low gain, simple piece of equipment. The equipment being considered in this thesis is heavy and complex.

Indications of trends in the data over time are that future equipments will have these same two characteristics. With the independent variables WT, GAIN, and CPLX as one would suspect, an increase in the value of any of the three will increase the development cost. The negative coefficient of the active dummy variable indicates that active equipment tend to be less expensive to develop for a given weight, gain, and complexity than passive equipment. This is understandable when one considers the different uses to which active and passive equipments are put. Active equipment is designed for a specific or a few specific types of manipulation of incoming signals over a small band of frequencies, then retransmission of these signals. Passive equipment on the other hand is used for the evaluation and identification of incoming signals over a very wide range of frequencies. The processing in this case must maintain the signal characteristics so that accurate identification may be made.



SYSTEM DEVELOPMENT COST

in millions of 1975 dollars

GRAPH 1

When residual plots were examined, neither outliers nor indication of a need for a transformation were found. Many transformations were tried however in an attempt to improve the model, but no improvement was noted. There are two computed values for development cost with negative signs. The equipment in question in each case is very simple and light, two hundred (200) pounds in the first case and twenty-five (25) pounds in the other, and thus in a range of little concern in this thesis.

	ACTUAL DEVC	COMPUTED DEVC	RESIDUAL
SLQ19	1886.0999	148.4023	1737.6975
SLQ26	3654.0000	4915.4297	-1261.4297
SLQ28	11694.0000	11823.8711	-129.8711
SLQ30	1707.0000	1807.3008	-100.3008
$SLQ30_2$	1600.0000	1343.2773	256.7227
SLQ12A	1754.0000	2223.4141	-469.4141
SLQ17	7256.0000	7289.4141	-33.4141
SLQ12	380.0000	-90.0703	470.0703
WLR1	3598.0000	4770.0430	-1172.0430
WLR3	45.0000	-570.6680	615.6680
WLR8	11694.0000	9814.2344	1879.7656
WLR11	360.0000	2153.4727	-1793.4727

The standard error of estimate of this CER is very large, but is considered acceptable in light of the wide range of development costs, forty-five thousand dollars ($45,000) to eleven million six hundred ninety-four thousand dollars ($11,694,000), and the small size of the data base.

B. PROCUREMENT COST

1. Development Cost Excluded

The data base for procurement cost contained all twenty-one (21) pieces of equipment. The correlation matrix,

listed below, showed that weight, volume, and complexity are very highly correlated with procurement costs and again both complexity and weight are highly correlated with volume.

PROC	YR	WT	VOL	SENS	KWO	
1.000	0.542	0.920	0.920	0.407	0.593	PROC
	1.000	0.372	0.492	0.072	0.465	YR
		1.000	0.878	0.513	0.589	WT
			1.000	0.350	0.642	VOL
				1.000	0.519	SENS
					1.000	KWO

GAIN	ACT	CPLX	LG	SM	
0.286	0.271	0.735	-0.230	-0.210	PROC
0.169	0.151	0.554	-0.421	-0.435	YR
0.195	0.320	0.602	-0.125	-0.281	WT
0.257	0.361	0.787	-0.355	-0.127	VOL
-0.144	0.755	0.074	0.036	-0.307	SENS
-0.013	0.477	0.349	-0.508	-0.207	KWO
1.000	-0.122	0.068	-0.347	-0.007	GAIN
	1.000	0.328	-0.258	-0.208	ACT
		1.000	-0.314	-0.144	CPLX
			1.000	-0.085	LG
				1.000	SM

When regression analysis was performed on the data, the first four steps took in variables WT, CPLX, YR, and SM in that order. Any one of the steps furnishes a very satisfactory model, however step four results in the best. The fit in this case is exceptional and once again follows one's intuition.

The CER was:

$$PROC = -726.24341 + .22550\ WT + 349.72095\ CPLX + 67.14648\ YR + 324.85962\ SM$$

which had the following statistics

$R^2 = .959$

R^2 (adjusted) is a monotonic increasing function with a final value of .9487

Standard error of estimate = 276.8726

Mean value of the dependent variable = 956.82

F ratio = 93.651

Table value $F_{(.95;\ 4,\ 17)} = 2.96$

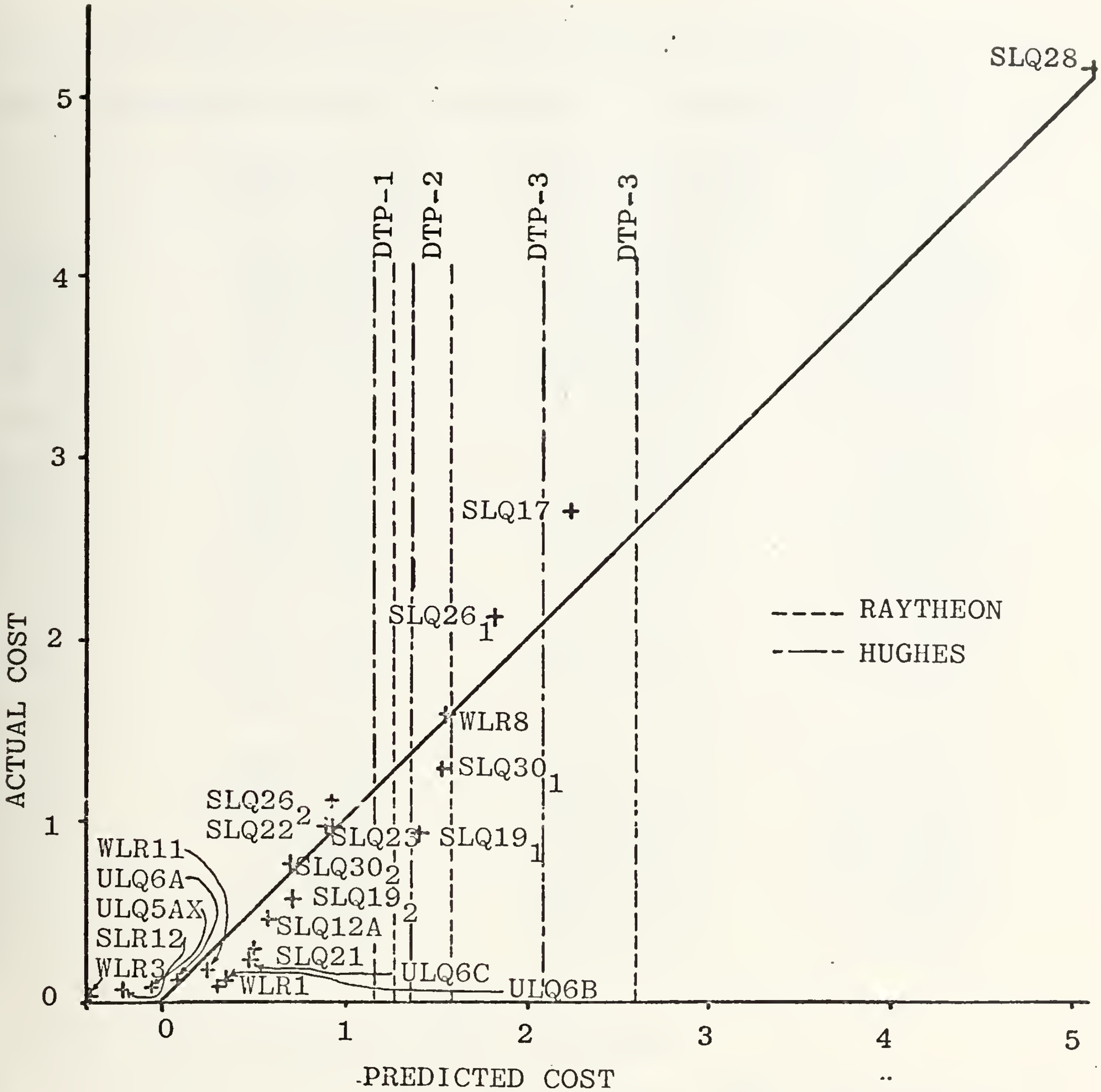
F value for each independent variable is:

WT	152.7812
CPLX	4.0917
YR	10.3247
SM	5.1110

Table value $F_{(.90;\ 1,\ 17)} = 3.03$

As in the previous CER, the constant has a negative sign and is acceptable for the same reasons. The positive coefficients for WT and CPLX are as one would suspect since generally procurement costs rise as the values for those two independent variables increase. The positive coefficient for the dummy variable SM indicates that if a piece of equipment is being designed for use on destroyer and smaller ships, it is more expensive than those developed solely for larger ships. Those units which are designed for use on smaller ships are generally more compact and consequently more expensive to fabricate for a given weight. Variable YR also has a positive coefficient which can be explained by the fact that over the years included in the data base, prices for procurement have increased more than can be explained by weight and complexity.

As can be seen from the table below, the computed first unit cost for three systems is negative, however since the three units concerned are of relatively low cost, they do not detract from the CER. It is also interesting to note that



SYSTEM FIRST UNIT COST

in millions of 1975 dollars

GRAPH 2

two of the three equipments with negative residuals are the same ones with negatives residuals for development cost.

	ACTUAL PROC	COMPUTED PROC	RESIDUAL
ULQ5AX	99.0800	-45.6897	144.7697
ULQ6A	128.2400	107.6472	20.5928
ULQ6B	130.6000	346.9700	-216.3700
ULQ6C	225.2800	475.0002	-249.7202
$SLQ19_1$	935.7998	1468.3806	-532.5808
$SLQ19_2$	588.0198	717.5596	-129.5398
SLQ22	959.0698	930.2021	28.8677
SLQ23	961.9900	900.8877	61.1023
SLQ24	359.6499	500.4072	-140.7573
$SLQ26_1$	2156.3799	1896.6470	259.7329
$SLQ26_2$	1120.7100	930.7031	190.0068
SLQ28	5226.1367	5199.8320	26.3047
$SLQ30_1$	1304.1199	1551.7834	-247.6636
$SLQ30_2$	821.6099	773.4519	48.1580
SLQ12	453.0898	618.9177	-165.8279
SLQ17	2725.0898	2269.3391	455.7507
SLR12	16.3000	-275.1497	291.4495
WLR1	79.3000	336.6997	-257.3997
WLR3	7.4600	-448.9043	456.3643
WLR8	1613.0198	1572.1064	40.9133
WLR11	175.0700	259.1987	-84.1287

2. <u>With Development Cost Included</u>

Although the author did not feel that using development cost, calculated by use of the CER in paragraph A, with the obvious uncertainty involved, was a good variable to be used in explaining the cost of procuring the first unit, he did feel that after a piece of equipment had been under development for a while a more accurate estimate of development cost would be available and could be used for that purpose. For that reason, regression analysis was performed using the twelve pieces of equipment for which development costs were known.

Although no acceptable CER was found, an interesting phenomenon occurred when the stepwise regression program was allowed to run with low F-level values and is presented here to demonstrate a problem concerned with high intercorrelations in a data base. The equations resulting from the various early steps were unacceptable due to very low F values for the individual variables. The values for R^2 and $R^2_{\text{(adjusted)}}$ increased continually and the standard error of estimate continued to decrease. Then suddenly at step nine, everything fit together and the F values of all the variables increased sharply. The following model was the result of that step:

$$\text{PROC} = 2811.59351 + .05553\ \text{DEVC} + .02824\ \text{WT} + 3.81016\ \text{VOL} + 25.98703\ \text{SENS} + 73.68718\ \text{KWO} + 77.15399\ \text{GAIN} - 1667.51343\ \text{ACT} - 1027.33765\ \text{LG} - 1718.32324\ \text{SM}$$

which had the following statistics:

$R^2 = .9997$

$R^2_{\text{(adjusted)}}$ is a monotonic increasing function with a final value of .9973

Standard error of estimate = 65.119

Mean value of the dependent variable = 1291.67

F ratio = 666.08

Table value $F_{(.95;\ 9,\ 3)} = 8.81$

F value for each independent variable:

DEVC	5.6128
WT	4.2697
VOL	31.925
SENS	67.1465
KWO	102.7486
GAIN	130.7182
ACT	62.6125
LG	41.8613
SM	133.5989

Table value $F_{(.80;\ 1,3)} = 2.68$.

At first glance, one would think this CER was exceptional; it does describe the data base very very well as shown by the statistics. However, if one examines the model itself and attempts to explain the coefficients, problems appear.

One would have trouble explaining why an increase in the sensitivity of a piece of equipment that is a more negative number, would decrease the price, and why a piece of equipment designed for use on both a small and large ship with all other variables constant would be $1.7 million cheaper per copy than one designed solely for large ships. Obviously the signs of the coefficients cannot be explained except by multicollinearity, correlation between the independent variables in such a way that the different variables interact in the model to balance each other, and thus describe the particular data base extremely well. It must be remembered that the data set is small (12) and that nine parameters are used in the model. If one were sure that the intercorrelation experience in the past data would also occur in future equipment, this model could be used to good advantage; however, it is felt that such assurance is difficult to attain and should not be assumed.

C. INSTALLATION COST ESTIMATING RELATIONSHIP

Examining the data base, one finds that there is an installation cost available for nineteen of the equipments, however, since the SLQ 22, SLQ 23, and SLQ 24 were never

installed on any ship and since the estimated installation cost for each were higher than any other equipment in the data base, those three equipments were excluded from the data base used for this CER.

Study of the correlation matrix, listed below, and scatter plots of the independent variables against installation cost offered only a preview of difficulties to come.

INST	YR	WT	VOL	SENS	KWO	
1.000	0.203	0.666	0.618	-0.338	0.414	INST
	1.000	0.368	0.449	-0.317	0.559	YR
		1.000	0.882	-0.624	0.615	WT
			1.000	-0.518	0.712	VOL
				1.000	-0.575	SENS
					1.000	KWO

GAIN	ACT	CPLX	LG	SM	
0.107	0.044	0.603	-0.119	-0.157	INST
0.176	0.174	0.439	-0.347	-0.515	YR
0.249	0.296	0.688	-0.137	-0.306	WT
0.331	0.366	0.829	-0.389	-0.137	VOL
0.097	-0.805	-0.497	0.158	0.289	SENS
-0.022	0.408	0.516	-0.589	-0.042	KWO
1.000	-0.069	0.139	-0.271	0.097	GAIN
	1.000	0.489	-0.324	0.022	ACT
		1.000	-0.262	-0.262	CPLX
			1.000	-0.455	LG
				1.000	SM

No variable was highly correlated with installation cost, however, several independent variables were highly correlated with each other.

When regression analysis was applied to the data, another interesting phenomenon occurred. First WT was taken into the model giving reasonable but poor statistics. During the next three steps, CPLX, ACT and SENS entered, in that order,

leaving an equation at the end of each step which was unacceptable due to low F values. On step five, WT was removed from the model and the statistics improved considerably. The CER at that step was:

$$INST = 331.97876 + 254.31705\ CPLX - 356.32886\ ACT + 8.42499\ SENS$$

which had the following statistics

$R^2 = .593$

R^2 (adjusted) is a monotonic increasing function with a final value of .4913

Standard error of estimate = 125.42

Mean value of the dependent variable = 195.86

F ratio = 5.828

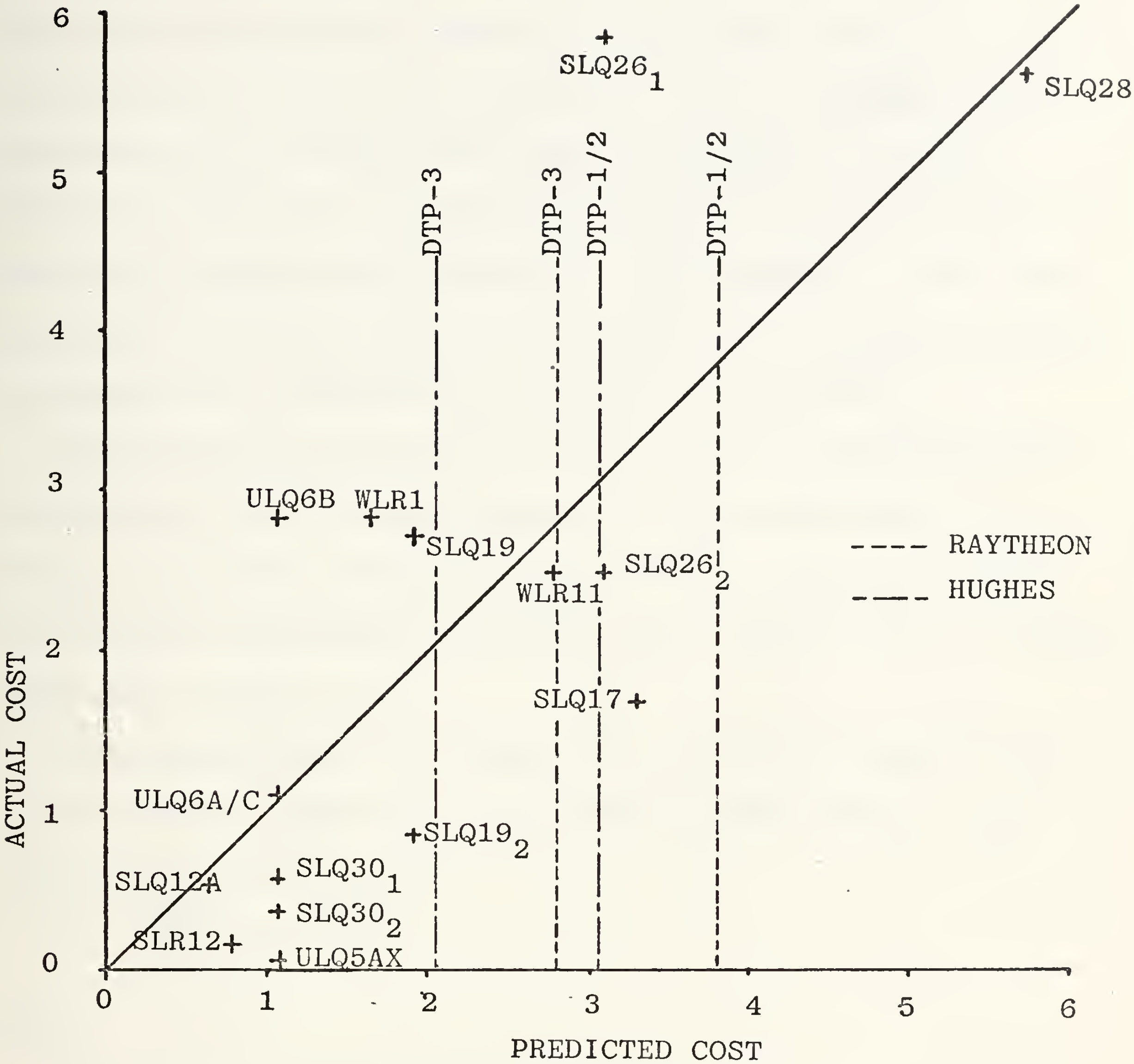
Table value $F_{(.95;\ 3,\ 13)} = 3.41$

F level of each independent variable:

CPLX	9.7667
ACT	6.7163
SENS	4.3534

Table value $F_{(.90;\ 1,\ 13)} = 3.14$

The statistics for this CER are acceptable. As was indicated in the development CER, the passive equipment tends to be more expensive to install than active and increasing complexity of a unit, of course, increases the installation cost. A contradiction, however, does appear in the sensitivity coefficient. Since the sensitivity variable is measured in negative decibels, the more negative, the higher the sensitivity; intuition would require that the coefficient have a negative sign. In this case, increasing the sensitivity



SYSTEM INSTALLATION COST
in hundred thousands of 1975 dollars

GRAPH 3

decreases installation cost. Examining the correlation matrix again, it is found that sensitivity is highly negatively correlated with the active variable. This is easily understood when one realizes that passive equipment has high receiver sensitivity in order to maintain incoming signals at sufficient quality for evaluation. The assumption that this negative intercorrelation will remain true in future equipment is reasonable, consequently this CER is acceptable.

Considerable investigation using various transformations of variables made no improvement over the above CER, so an attempt was made to find a better CER by a graphical method of selecting independent variables for inclusion by C.L Mallows described in Ref. 3.

This method uses a statistic, C_p, which measures the sum of the squared biases plus the squared random error. C_p is calculated by the formula:

$$C_p = \frac{RSS}{s^2} - (N - 2_p)$$

where

RSS is the residual sum of squares

s^2 is a good unbiased estimate of the variance of the random error inherent in the dependent variable

N is the number of data points

p is the number of terms in the equation

Reference 3 determines an estimator for s^2 from an equation with all of the independent variables included. A forty-five degree straight line is drawn on a graph of number

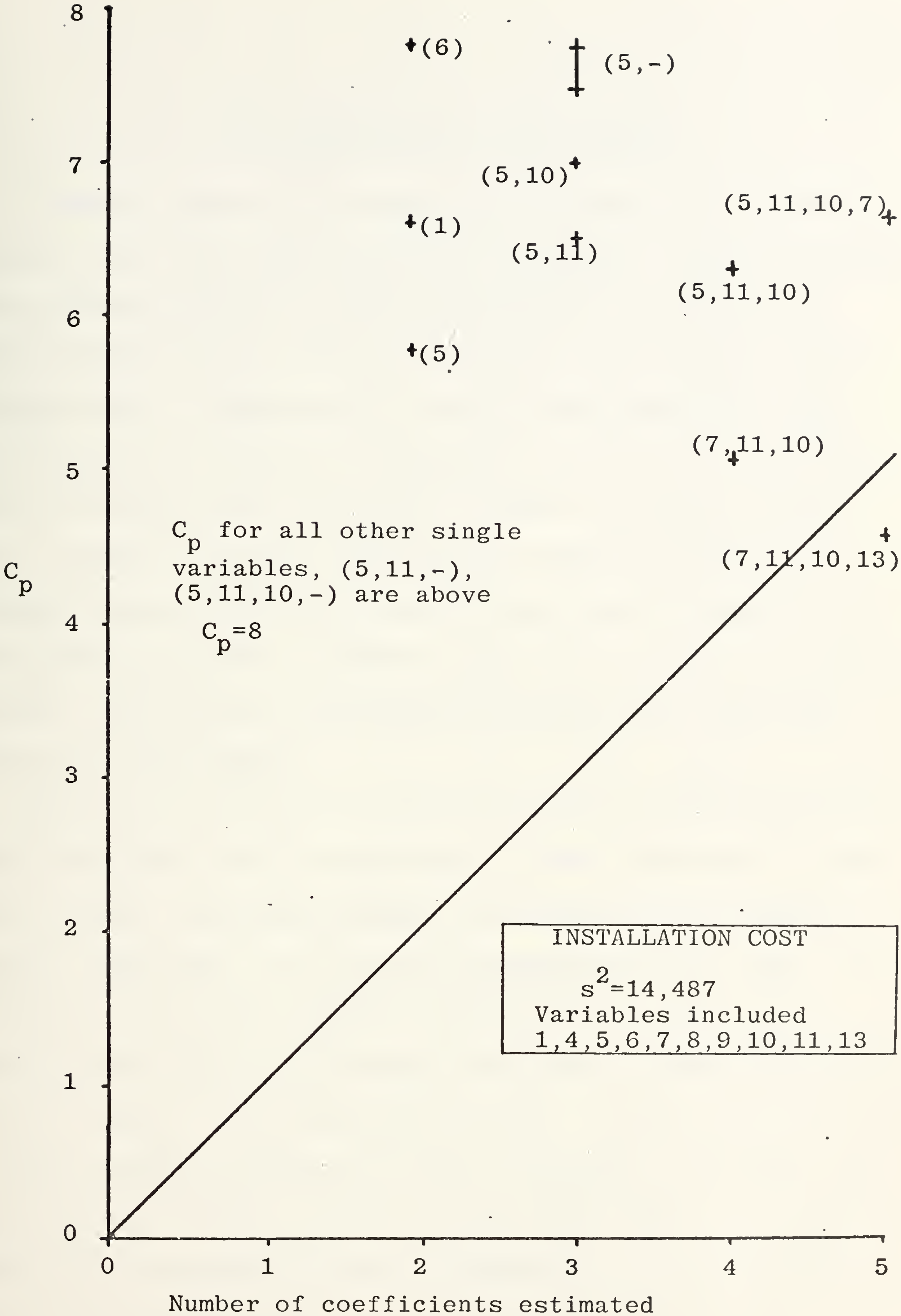
of variables included versus C_p from the origin. This is done since for p variables with negligible bias, $C_p = p$. The distance from the horizontal axis to that line is random error and above it is bias error. At this point a C_p is calculated for each possible equation containing one variable. The equation with the lowest C_p contains the first variable to be included in the final model. Next C_p's are calculated for all models including the first variable and one of the remaining variables. The equation with the lowest C_p contains the first variable selected plus the second variable to be included in the final model. This process is continued adding one additional variable each step until all the variables are included. At this point there is one best equation for each step from which one must select the best model; in most cases it is the one with the lowest C_p value regardless of whether the point is above or below the line. Normally one is willing to accept some bias in order to minimize variance.

This method was attempted using the installation cost data with the hope that using C_p to select independent variables would give better results than using correlation as used in stepwise regression analysis. It was felt that the model with all variables included did not explain the dependent variable very well and the statistic from that regression confirmed it. That estimate of variance, s^2, as well as estimates of variance derived from several other regression equations were used in the formula for C_p, however,

none of the results improved upon the model developed through stepwise regression.

As a matter of fact, since the graphical method does not allow for removal of variables, as was used in the step regression analysis, the best model found by the C_p analysis was one with WT and a constant only.

One could use the long method, calculating C_p for each of the 2^{10} possible combinations of variables, but it is not felt that the results would be worth the enormous amount of calcualtions required. Graph 4 shows the best results attained using Mallows method. The estimate of variance used is the minimum encountered during investigations of the various models for the installation CER. As can be seen, the process was only carried out to four variables. At that stage, two points (7, 11, 10) and (7, 11, 10, 13), found by stepwise regression but not by the C_p analysis, were below what should have been the minimum C_p at each of steps three and four. It is obvious that this method will not be of use on data with high intercorrelation until a way of removing variables is included.


8
7
6
5
4
3
2
1
0
(6)
(5,-)
(5,10)
(1)
(5,11)
(5,11,10,7)
(5,11,10)
(5)
(7,11,10)
(7,11,10,13)
C_p
C_p for all other single variables, (5,11,-), (5,11,10,-) are above C_p=8
INSTALLATION COST
s^2=14,487
Variables included
1,4,5,6,7,8,9,10,11,13
0
1
2
3
4
5
Number of coefficients estimated

GRAPH 4

IV. COST COMPUTATIONS AND ANALYSIS

Presently under the Design-to-Price Electronic Warfare Program (DTP EW), Hughes Aircraft Company and Raytheon Company are each developing an electronic warfare system for the United States Navy. These systems are to have three stand-alone levels of operational capacity designated DTP-1, the least expensive, DTP-2, a moderately priced suite, and DPT-3, which includes DTP-1 and DTP-2. Present contracts require each company to develop and build two DTP-3 prototypes. Production decisions will then be made based on competitive prototype evaluation. Present plans are to build one hundred sixteen (116) DTP-1, one hundred-eighteen (118) DTP-2 and fifty-nine (59) DTP-3.

Since the contract is a design-to-price type, prices have been specified, and the equipment is being developed to meet those prices. The cost targets are three hundred thousand dollars ($300,000), five hundred thousand dollars ($500,000) and one million four hundred thousand dollars ($1,400,000) respectively and are to include comulative average production, initial spares, and installation costs. Translating cumulative average production costs to first unit cost, the targets are six hundred eighteen thousand dollars ($618,000), one million thirty-two thousand dollars ($1,032,000), and two million two hundred thirty-five thousand dollars ($2,235,000).

All price estimates in this section were calculated using up-to-date parametric information received from PME 107X on 19 February, 1975 as follows:

RAYTHEON

	YR	WT	SENS	GAIN	ACT	CPLX	SM
DTP-1	6	2458	-55	22	0	2	1
DTP-2	6	3932	-55	22	0	2	1
DTP-3	6	8331	-55	22	1	3	0

HUGHES

	YR	WT	SENS	GAIN	ACT	CPLX	SM
DTP-1	6	2095	-63	20	0	2	1
DTP-2	6	2933	-63	20	0	2	1
DTP-3	6	6036	-63	14	1	3	0

All cost estimates are in thousands of 1975 dollars. Prediction interval (PI) are calculated for ninety-five percent confidence for each CER.

A. DEVELOPMENT COST ESTIMATES

The following development cost estimates were calculated using indicated CER in column one and two and are the program managers estimates as of 19 February 1975 in the last column.

	THESIS CER PI (± 3220)	REFERENCE 1 CER PI (± 2406)	PME 107 X
RAYTHEON	8990.77	5055.95	16,298
HUGHES	7157.65	3663.47	14,914
Total	16148.42	8719.42	31,212

The CER from Ref. 1 is;

$$DEVC = 3.52335 + 1.92814\ PROC_1$$

$PROC_1$ is the first unit price as determined by Ref. 1 procurement CER number 1. The estimates using CERs are much lower prices than the program manager estimate. This is due to the fact that instead of just developing a system capable of one operational level as is the case in the data base, DTP-3 must be developed to operate at three levels. The calculations of development cost in Ref. 1 used a ninety percent cumulative learning for the development of two DTP-3 systems. Since they are identical, logic would indicate that there would be no development cost for the second unit. It is interesting to note however, that by applying the learning curve, the CER from this thesis gives cost figures very close to those estimated by PME 107X as can be seen in the following table. The ninety percent learning was applied to columns one and two.

	THESIS CER	REFERENCE 1 CER	PME 107X
RAYTHEON	16,183.38	9,100.7	16,298
HUGHES	12,883.77	6,594.24	14,914
TOTAL	29,067.15	15,694.94	31,212

B. FIRST UNIT PROCUREMENT COST ESTIMATES

First unit procurement cost estimates were calculated using the CER as indicated in columns one and two. Column three contains the program's manager estimate of first unit procurement cost as of 19 February 1975.

THESIS CER PI(± 584.2)	REF 1 CER $_1$/CER$_2$ PI(± 1080/$_{\pm 1086}$)	PME 107X
RAYTHEON		
DTP-1 1255.22	774.79/$_{839.51}$	496.13
DTP-2 1587.55	1238.49/$_{1287.36}$	947.20
DTP-3 2604.44	2622.19/$_{2623.93}$	2005.32
HUGHES		
DTP-1 1173.36	660.74/$_{728.54}$	513.41
DTP-2 1362.33	924.34/$_{983.83}$	880.24
DTP-3 2086.92	1900.44/$_{1926.63}$	2261.10

Ref. 1 used two CERs to estimate procurement cost, they are:

$$PROC_1 = -1207.12 + .314561\ WT - 18.7253\ SENS + 6.62988\ ERP$$

and

$$PROC_2 = 92.6764 + .303836\ WT$$

ERP is effective radiated power.

It would be impossible to explain the differences in prices between the three price estimates for each manufacturer's equipment in prices except to say that each was derived using a different estimator. In the case of Ref. 1, a smaller number of data point were used in determining each CER than this thesis. It is interesting to note that the CER developed in this thesis estimates consistantly $600,000 above PME 107X except for the Hughes DTP-3 for which the estimate is under PME 107X.

C. INSTALLATION COST ESTIMATE

The cost estimates for installation costs in column one and two are calculated by the CER as indicated. Column three contains the program managers estimates as of 19 February 1975.

	THESIS CER PI($\pm$270.9)	REF. 1 CER PI($\pm$318.3)	PME 107X
RAYTHEON			
DTP-1	377.24	187.68	43.15
DTP-2	377.24	239.00	52.79
DTP-3	275.23	359.38	274.83
HUGHES			
DTP-1	309.83	189.65	56.1
DTP-2	309.83	231.38	65.2
DTP-3	207.81	388.48	145.2

Ref. 1 used a CER based on first unit costs as estimated by PME 107X; the CER is:

$$INST = 131.24 + .113768\ PROC$$

In this case the large discrepency between the thesis estimate and PME 107X estimate is very easy to explain. First of all, the equipment is to be installed by the manufacturer while the ships are dockside at a Navy base rather than the usual practice of having it installed by shipyard personnel in Naval Shipyards. Secondly, as can be seen from the last section, the installation CER, although seemingly the best available from the data, is not particularly good.

As can be seen from the cost estimates, the CER developed in this thesis predicts that DTP-3 installation cost will be less than either DTP-1, or DTP-2; however, this could not be correct since DTP-3 includes DTP-1 and DTP-2. This demonstrates

one of the problems that occur when one attempts to predict the cost of a system which is different than the equipment in the data base. Since the active coefficient has a negative sign with all other variables in the CER held constant, the active equipment DTP-3, installation cost estimate is less.

D. SUMMARY AND CONCLUSIONS

Cost Estimating Relationships are only as good as the data base from which they are derived. When applying them, one must be aware of whether the proposed system is within or is an extension beyond the data base. The larger the step beyond the data base, the more uncertain the results.

In the case of the DTP EW program, many things are different than past equipments, consequently the need for more detailed costing is obvious. Installation costs, in particular, require a very detailed study since the whole idea of contractor installed equipment is new in EW equipment.

This thesis estimated the costs development, first unit procurement and installation costs for the DTP EW system. The cost estimates for development cost, although lower than those predicted by the program manager, are acceptable when one understands the difference between development of equipment in the past and the DTP system. The procurement cost estimated by this thesis is consistantly $600,000 above the program manager estimates. The difference can only be explained by the fact that the prices were derived from

different estimators, In the case of installation cost estimates, the thesis CER estimates consistantly above program manager's estimates, however since the new equipment is to be contractor installed vice Naval Shipyard installed the difference would be expected.

APPENDIX: DATA BASE, SOURCE, AND ADJUSTMENTS

The comprehensive data matrix of surface electronic warfare equipments, Table 1, was taken from Ref. 1. A considerable attempt was made to validate the particular numbers in the matrix, however, it was found that a validation of the cost figures, in most cases, would be impossible due to a lack of accurate documentation for the earlier equipments. The Air Force Electronic Countermeasures Directory, Ref. 4, was the only publication giving specific parametric information for all the systems, however, both the weight and volume figures differed considerably, in some cases as much as a factor of fourteen for WT, and ten for VOL. The data used in this thesis included the total package for a ship, while the figure given in the ECM Directory was only for the black box, antenna was not included nor were two units accounted for when two units were required per ship.

Reference 1 stated that a 90% log linear cumulative average learning curve was assumed for EW equipment and used throughout that paper. It was decided that first unit procurement cost should be used, since different quantities of each equipment were purchased. Average unit costs and quantity were assumed to be correct and calculations were made to insure a ninety percent average learning curve was in fact used. These calculations indicated learning curves ranging from 80% to 90% with the great majority falling into the

84-86% range. The author of Ref. 1 charged with calculations could not explain the discrepency and stated that it could have been an error in his method of calculation. Consequently, first unit costs were recalculated using a 90% curve, average unit costs, and quantity purchased, except in the case of SLQ 22, SLQ 23, and SLQ 24 for which quantity purchased was zero; in that case first unit costs given in Ref. 1 were used. The author decided on 1969 vice 1900 as a base year and transformed the YR variable to conform.

It was felt that a measure of complexity should be included as a possible independent variable. Mr. John P. Obrien, an Electronics Engineer in the Design-to-Price Office of Navy Electronic Systems Command PME 107X gave his expert opinion of each of the equipments in the data base as well as those three under development by Raytheon and Hughes. Each piece of equipment was given numerical value of complexity ranging from 1, simple, through 2, moderately complex, to 3 very complex. His evaluation was validated by other engineers in his office.

Since the data base contained both passive and active equipments, a dummy variable with a value of one for active and zero for passive equipment was included. The only other possible difference between the equipment that it was felt could have some influence cost was the size ship the particular equipment was designed for. Two dummy variables were used to take this difference into account. The LG variable very simply was one if the equipment was designed for use on

Guided Missile Destroyers or larger ships and zero otherwise. Similarly the SM variable was one if the equipment was designed for destroyer or smaller ships.

Table 2 is a listing of the data matrix as used in this thesis. Blanks in the matrix are data which is not available.

TABLE 1

ELECTRONIC WARFARE EQUIPMENT DATA MATRIX

SYSTEM	UNIT COST	YEAR	DEVC	INST	WT	VOL	SENS	KWO	QUANTITY	GAIN
ULQ-5AX	50	62	N/A	20.2	560	36.6	-45	.70	90	0
ULQ-6A	60	62	N/A	113.9	1240	81.6	-45	.75	148	6
ULQ-6B	53.4	65	N/A	282.9	1408	115.4	-45	.75	359	6
ULQ-6C	101.8	66	N/A	113.9	1678	94.1	-45	.75	186	6
$SLQ\text{-}19_1$	758	69	1886.1	268.1	5190	275.2	-35	15.0	4	0
$SLQ\text{-}19_2$	452	69	N/A	N/A	3301	150.4	-35	15.0	4	0
SLQ-22	656	69	N/A	609.0	4244	180.4	-45	15.0	0	15
SLQ-23	658	69	N/A	609.0	4114	180.6	-45	15.0	0	15
SLQ-24	246	69	N/A	609.0	2338	136.6	-45	1.0	0	15
$SLQ\text{-}26_1$	1572	70	3654	582.5	6016	262.1	-36	15.0	8	15
$SLQ\text{-}26_2$	817	70	N/A	248.0	3173	194.4	-36	1.0	8	15
SLQ-28	4092	71	11694	562.5	21032	560.7	-20	15.0	5	15
$SLQ\text{-}30_1$	919	74	1707	58.4	4071	181.9	-45	15.0	10	14
$SLQ\text{-}30_2$	408	74	1600	37.0	2060	131.6	-45	1.0	100	15
SLQ-12A	250	65	1754	52.1	2614	154.2	-50	.4	50	20
SLQ-17	1625	73	7256	168.9	6000	450	-48	15.0	30	15
SLR-12	6.8	65	380	15.0	200	12	-60	N/A	315	18
WLR-1	30.0	63	3598	280.1	1958	185	-80	N/A	600	15
WLR-3	3.0	63	45	N/A	25	1	-45	N/A	400	15
WLR-8	1200	73	11694	N/A	2908	220	-85	N/A	7	15
WLR-11	120	72	360	245.3	375	16	-65	N/A	12	0

TABLE 2

ELECTRONIC WARFARE EQUIPMENT DATA MATRIX

SYSTEM	DEVC	PROC	INST	YR	WT	VOL	-SENS	KWO	GAIN	ACT	CPLX	LG	SM
ULQ-5AX	0	99.08	20.2	-7	560	36.6	-45	.70	0	1.00	2.0	1.0	1.0
ULQ-6A	0	128.24	113.9	-7	1240	81.6	-45	.75	6.0	1.00	2.0	1.0	1.0
ULQ-6B	0	130.60	282.9	-4	1408	115.4	-45	.75	6.0	1.00	2.0	1.0	1.0
ULQ-6C	0	225.28	113.9	-3	1678	94.1	-45	.75	6.0	1.00	2.0	1.0	1.0
$SLQ-19_1$	1886.1	935.80	268.1	0	5190	275.2	-35	15.00	0	1.00	2.0	0	1.0
$SLQ-19_2$	0	588.02	85.0	0	3301	150.4	-35	15.00	0	1.00	2.0	1.0	0
SLQ-22	0	959.07	609.0	0	4244	180.4	-45	15.00	15.0	1.00	2.0	0	0
SLQ-23	0	961.99	609.0	0	4114	180.6	-45	15.00	15.0	1.00	2.0	0	0
SLQ-24	0	359.65	609.0	0	2338	136.6	-45	1.00	15.0	1.00	2.0	0	0
$SLQ-26_1$	3654.0	2156.38	582.5	1	6016	262.1	-36	15.00	15.0	1.00	2.5	0	1.0
$SLQ-26_2$	0	1120.71	248.0	1	3173	194.4	-36	1.00	15.0	1.00	2.5	1.0	0
SLQ-28	11694.0	5226.14	562.5	2	21032	560.7	-20	15.00	15.0	1.00	3.0	1.0	0
$SLQ-30_1$	1707.0	1304.12	58.4	5	4071	181.9	-45	15.00	14.0	1.00	2.0	0	1.0
$SLQ-30_2$	1600.0	821.61	37.0	5	2060	131.6	-45	1.00	15.0	1.00	2.0	1.0	0
SLQ-12A	1754.0	453.09	52.1	-4	2614	154.2	-50	0.40	20.0	1.00	2.0	0	1.0
SLQ-17	7256.0	2725.09	168.9	4	6000	450.0	-48	15.00	15.0	1.00	3.0	0	1.0
SLR-12	380.0	16.30	15.0	-4	200	12.0	-60	0	18.0	0	1.0	1.0	1.0
WLR-1	3598.0	79.30	280.1	-6	1958	185.0	-80	0	15.0	0	2.0	1.0	1.0
WLR-3	45.0	7.46	0	-6	25	1.0	-45	0	15.0	0	1.0	1.0	1.0
WLR-8	11694.0	1613.02	0	4	2908	220.0	-85	0	15.0	0	3.0	0	1.0
WLR-11	360.0	175.07	245.3	3	375	16.0	-65	0	0	0	2.0	1.0	0

LIST OF REFERENCES

1. Mitchell, W. T. and Mullins, J.D., Independent Cost Analysis for Design-to-Price EW Suites, U.S. Navy Systems Analysis Division, Resource Analysis Group, January, 1974.

2. BMD Biomedical Computer Programs (BIMEDO2R), University of California Publications in Automatic Computation, Publication Number 2, Second Edition, University of California at Los Angeles (UCLA), 1970.

3. Daniel, C. and Wood, F.S., Fitting Equations to Data, p. 86-99, Wiley, 1971.

4. Deleted.

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